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CALIBRATION PROCEDURE FOR SKIN SIMULANTS

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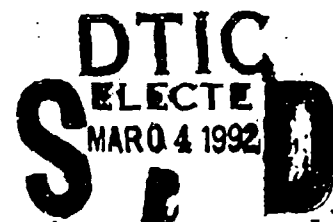
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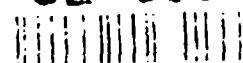
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PREFACE

This report describes a procedure for the calibration of inanimate sensors or "skin simulants". The simulants were constructed to simulate the thermal properties of skin and correlate burn severity with the temperature history at known depths of the skin. They are an essential part of the remote data collection component of The Advanced Thermal Response Data Acquisition and Analysis System being built by Natick. The work was done under the project "Thermal Protection, 1L162786AH98CAB00, administered by the Directed Energy Protection Branch (DEP Br), Physical Sciences Division (PSD)*, Soldier Science Directorate, U.S. Army Natick Research, Development and Engineering Center.

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All experimentation was conducted in the Directed Energy Protection Branch at the U.S. Army Natick Research, Development and Engineering Center. The citation of trade names in this report does not constitute official endorsement or approval of use of an item.

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CALIBRATION PROCEDURE FOR SKIN SIMULANTS

INTRODUCTION

A state-of-the-art data acquisition/instrumented manikin system is being built by the Physics & Engineering Branch at Natick to study how an individual soldier is protected from the thermal insults of flame, CO₂ lasers and thermonuclear weapons while wearing military uniform systems, items and fabrics. This manikin system can record data in a laboratory or remote field test setting. The data is formatted to a standard serial bit stream and can be sent for miles on a coaxial cable or transmitted on a standard FM transmitter for reception at extreme ranges. Using software tailored to the system, the researcher acquires data to be displayed in real time or stored for analysis of burn-severity predictions at any convenient future time. The data recorded from the experiments are used to generate two- and three-dimensional representations of the extent of skin burns as predicted from skin simulant recordings. A three-dimensional manikin display is capable of showing the progression of skin damage as it changes with time.

The system is called The Advanced Thermal Response Data Acquisition and Analysis System (ATRES/DAAS) and consists of four main units: 1) remote data collection sites, 2) master data collection control, conversion, and formatting, 3) data processing and storage, and 4) graphical analysis and presentation.

This work was initiated to support the implementation of the remote data collection sites of the ATRES/DAAS. These collection sites consist of three major parts: manikins, simulated skin sensors (simulants), and electronic hardware.

Essential components of the manikins are the skin simulants because they mimic the thermal properties of human skin. The data they produce determine the correlation of skin burn severity with the temperature history at known skin depths, i.e., the epidermal/dermal interface of the skin. These simulants are evenly distributed over the torso, arms, hands and legs of the manikins. If the simulants do not accurately indicate the thermal response of human skin, any data from a thermal radiation test source become inconclusive.

The simulants used in this study were patterned after the work of Derksen, et al. at the Naval Materials Laboratory (NML)¹ and made by the Fabric Research Laboratories Division of Albany International Corporation, Dedham, MA. The NML simulants consisted of approximately 40 percent by weight of fine silica powder mixed with alpha (α) cellulose urea formaldehyde. The mixture was molded under pressure in a hot press to form a button, 3.8 cm in diameter and 1.3 cm thick that was curved on one face. The mixture was also molded in the form of a disk 2.5 cm in diameter and 1.25 cm in thickness for placing in the skin of Natick's instrumented manikin. These sensors had a 0.001 cm-thick Type T (copper-constantan) thermocouple embedded 0.05 cm beneath the surface that provided a time-temperature history of the simulant's response to a thermal source.²

Natick has recently developed its own sensors for the multimanikin ATRES/DAAS using the NML simulant material but configured as disks with a 0.013 cm diameter bead thermistor placed 0.05 cm below the surface to obtain the temperature data. The sensors were made to reduce the fragility of the older simulants and increase response time and accuracy. These newly developed sensors had to be calibrated against a theoretical thermal model of actual skin.

An industrial CO₂ laser, Dash-8[™] data acquisition and controller board with EXP-16[™] multiplexer hardware and previously used NML sensors with known reliability were utilized in the development of Natick's system of calibration. This paper describes the theory, experimentation, and a finalized calibration technique.

ANALYTICAL MODEL

To calibrate the skin simulant, an analytical model of the dynamic thermal response of actual skin was used. The governing partial differential equation of heat transfer for transient flow is³:

$$K \nabla^2 T = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

where k is thermal conductivity, T is temperature, ρ is density, C_p is specific heat, and t is time. The skin simulant was designed to measure the temperature that would have existed at a depth of 100 micrometers (μm) beneath the surface of the skin. This is the approximate depth of the epidermal-dermal interface and the point at which the temperature will be found as a function of time. For this model, one dimensional heat flow will be assumed. For the 1-D case, Eq. 1 can be written as:

$$K \frac{\partial^2 T}{\partial x^2} = \rho C_p \frac{\partial T}{\partial t} \quad (2)$$

For the case of a finite pulse of radiation, Eq. 2 was solved by Roach et al. The solution is separated into two segments, one for the duration of the

radiation pulse and one for the cooling of the skin after the pulse. The solution of the equation for the radiation pulse phase is expressed in symbolic form as⁴:

$$w = \frac{h}{b} \left[\operatorname{erfc} \frac{x}{2\sqrt{\alpha t}} - \exp \left(\frac{bx}{k} \right) \exp \left(\frac{ab^2 t}{k^2} \right) \operatorname{erfc} \left[\frac{x}{2\sqrt{\alpha t}} + \frac{b}{k} \sqrt{\alpha t} \right] \right] \quad (3)$$

where w is the temperature at the interface, h is the irradiance, b is the heat transfer coefficient, and $\alpha = (k/\rho C)$ is the thermal diffusivity. After the radiation pulse ends, temperature during cooling is calculated by replacing h by a negative value at time $t = T$ (T is the finite pulse length) and adding (-) this portion to the above from $t = T \rightarrow \infty$.

Equations 2 and 3 were used in a computer program written in BASIC to plot the recorded temperature (from 0 to 7 seconds (s)) of the epidermal/dermal interface for any laser pulse power and length (Appendix A). The thermal parameters of human skin that were used in this computer solution are listed in Table 1.

Table 1. Thermal parameters of skin.

k = Thermal conductivity	= 0.00122 cal/cm-s-°C
C_p = Specific heat	= 0.87 cal/g-°C
ρ = Density	= 1.03 g/cm
x = Depth	= 0.01 cm
b = Heat transfer coeff	= 0.00015 cal/cm-s-°C

EXPERIMENTAL METHOD

A. Instrumentation

All experiments were conducted at the DEP Br, PSD, U.S. Army Natick Research, Development, and Engineering Center, Natick, MA. The following is a list and brief description of the equipment used to perform the experiments. The actual operation of the devices is detailed further in the Procedure and Analysis sections.

Laser - The laser used as a thermal radiation source was a Spectra-Physics Model 820EP Gas Transport Industrial CO₂ laser with the following specifications:

1. Wavelength: 10.6 μm , operating in CW TEM₀₀ (Continuous Wave, Transverse Electric and Magnetic Mode, lowest order)
2. Output power: 2500 watts (W) maximum
3. Beam diameter: 19 millimeters (mm) at the laser output mirror
4. Output power stability: $\pm 2\%$
5. Beam divergence stability (full angle): ± 0.15 milliradians (mrad)
6. Minimum shutter time (open and close): 50 milliseconds (ms)
7. Beam bender: A device designed to intercept and reflect the incident laser beam at right angles to its original direction. It was used to lower the laser beam to the height of the optical table.
8. Helium neon laser: An internal component of the CO₂ laser system was a 2 milliwatt (mW) HeNe laser used to align optical equipment, position work and direct the CO₂ beam.

Optics -

1. Beam Splitter and Lenses - A zinc selenide (ZnSe) coated beam-splitter (50/50) was used to divide the laser beam into two equal beams. ZnSe lenses were used to direct the laser beams to each kaleidoscope and sensor. The beam splitter and lenses were made by II-VI, Inc., Saxonburg, PA.
2. Kaleidoscope - A kaleidoscope or scrambler (a rectangular pipe light guide or optical conduit) constructed of naval bronze with a highly polished passage 1 cm high, 1 cm wide and 16 cm long was incorporated with the lenses in order to acquire a uniform beam energy profile. The kaleidoscopes were made by instrument makers at Natick.

Sensors - NML skin simulants that were used in previous Natick thermal experiments were used as the experimental targets. These sensors contained a type T thermocouple.

Calorimeters - HyCal Engineering, Santa Fe Springs, CA, Series C-1100 asymptotic calorimeters were used as heat flux sensors to record the amount of heat reaching the skin simulant. These calorimeters were calibrated by the manufacturer. They were coded by their serial numbers and supplied with their calibration curves that related voltage to Btu/ft^2-s .

Hardware -

1. HP9825B - The CO_2 laser and shutter were configured to operate from a Hewlett Packard Model 9825B desktop computer. With this arrangement, the experimenter operated the laser from a protected room removed from the laser.

Hardware (Cont'd)-

2. Compaq Model 320C2 PC - A portable Compaq Model 320C2 personal computer from COMPAQ[®] Computer Corporation, Houston, TX was used with data acquisition hardware and software. It provided both data gathering and data analysis support.
3. Dash-8 - A Dash-8 Data Acquisition and Control Interface Board was installed in the Compaq Model 320C2 PC to provide analog/digital interface and high speed data acquisition.
4. EXP-16 - An Expansion Multiplexer and Instrumentation Amplifier (EXP-16) were used to extend the capabilities of the DASH-8. Using this system data were accepted simultaneously from both the sensors and calorimeters. The DASH-8 and EXP-16 are products of MetraByte Corporation, Taunton, MA.

Software -

1. Labtech Notebook[®] - A software package from Laboratory Technologies Corporation, Wilmington, MA was designed to interface with the Dash-8 and EXP-16. The sampling rate, sampling duration, input channels, and data destination were among the variables controlled by Labtech Notebook.
2. Lotus 1-2-3[®] - Data files generated by Labtech notebook were formatted for a direct link to Lotus 1-2-3. Lotus 1-2-3, a software package of LOTUS, Cambridge, MA, provided spreadsheet power, numerical analysis, and graphing capabilities. Lotus's ability to import files allowed for the desired comparison of theoretical and experimental data.

B. Optical System

The beam shaping optical system was designed to produce a beam profile that was uniform over the sensor area of the skin simulant. This uniformity was necessary because, although the beam profile was approximately gaussian the profile tended to be more complex as the laser output power was increased. This tendency might have caused beam energy irregularities, which could affect the data acquired. In order to achieve the desired beam uniformity, a kaleidoscope was placed between two ZnSe lenses. The first lens has an effective focal length (EFL) of 63.5 mm and the second lens has an EFL of 127.0 mm. The emitted laser beam was directed through the 63.5 mm focal length ZnSe lens and into the kaleidoscope. The kaleidoscope divided the incoming wave fronts of the beam into rectangular segments approximately equal to the cross-sectional area of the pipe. These formed segments were superimposed at the output end. The result was a homogenized energy distribution at the exit aperture⁵. The 127.0 mm focal length ZnSe lens refocused the homogenized beam onto the skin simulant sensor. The irradiance density was changed by adjusting the distances between the lenses, kaleidoscope and simulant, and the irradiated area on the simulant.

Laser output power was determined by reading the digital display of the internal meter of the laser. Following a number of preliminary data runs, it was evident that a more precise method was needed to record the beam's power at the simulant (see C. Procedure). Thus, the optical system was changed to irradiate a calorimeter simultaneously with the skin simulant, as shown in Fig. 1.

Not to Scale

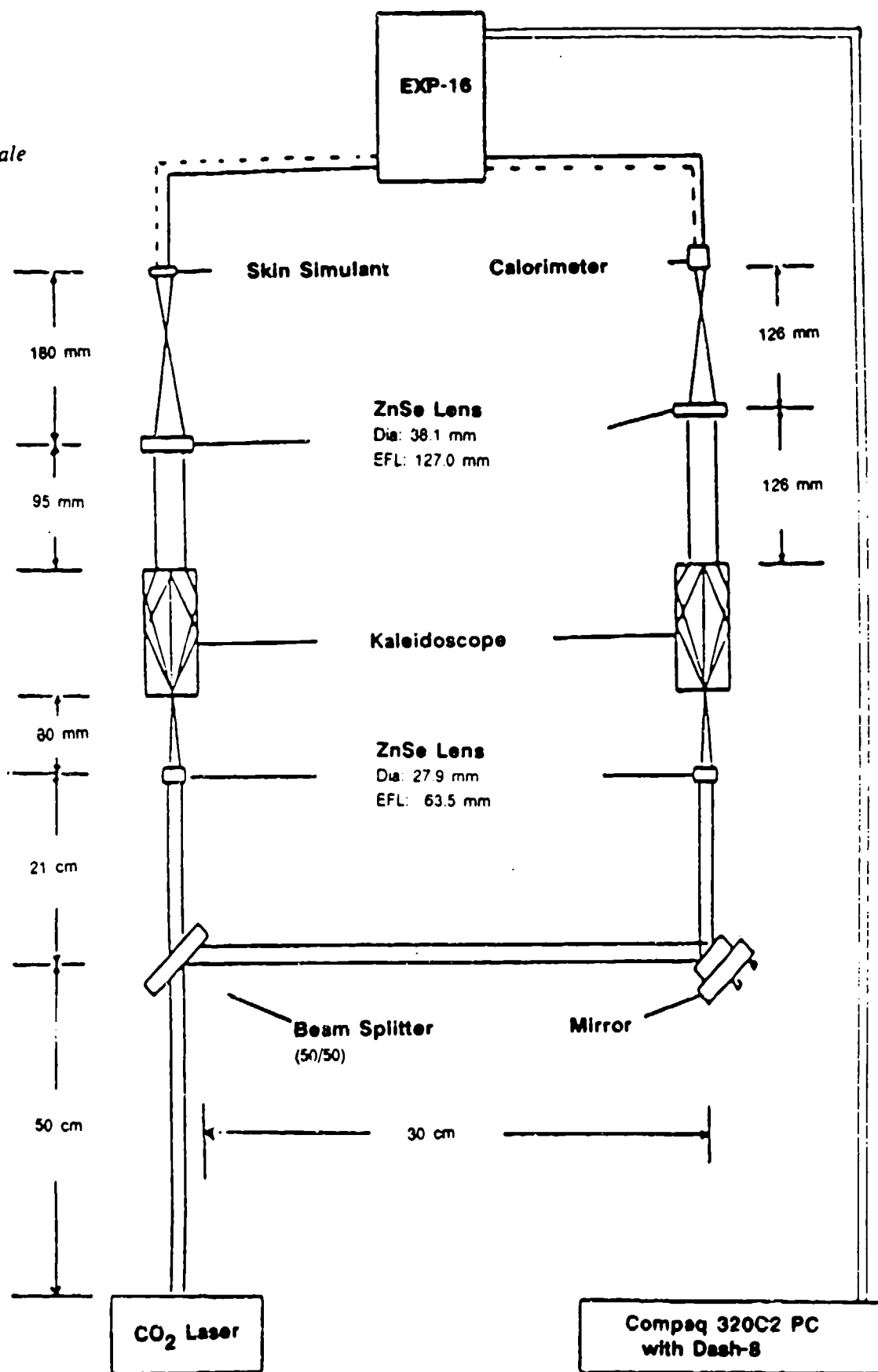


Fig. 1. Optical System for Calibrating Skin Simulants

The result was the arrangement illustrated in Fig. 1, in which the beam from the laser was split into two beams by a 50/50 ZnSe beam splitter. The beam directed through the optical system that was initially used was termed the primary beam and the beam redirected by the beam splitter was termed the secondary beam. The skin simulant sensor was irradiated by the primary beam. The beam splitter was used to change the direction of the secondary beam 90 degrees horizontally, toward a mirror which directed the secondary beam through a system of optics identical to those of the primary path. The calorimeter that was placed at the end of the secondary path was used to determine the laser beam's output power. With this system the beam distribution was made uniform and the irradiance regulated.

C. Procedure

Two of the objectives in the calibration procedure were 1) to use a CO₂ laser as a thermal source to obtain temperature vs. time data from the skin simulant, and 2) to record the power density and duration of the radiation impinging on the skin simulant for input in the analytical model.

For all experiments, the external membrane control panel on the laser was used to establish the desired lasing current and to transfer control of the laser to the HP9825B computer.

The sensors that were mounted in the primary and secondary beam paths sent voltage difference signals to the EXP-16 Multiplexer where the signal was amplified and sent to the Dash-8 data acquisition and controller interface board. The Dash-8 converted the signals from analog to digital format. Labtech Notebook was used to control the sampling rate and duration of the

voltage signal. Also, that software was used to display the real time voltage signal on a color monitor screen and store the data in specified ASCII files. Further analysis on the data was accomplished using Lotus 1-2-3.

The CO₂ laser system contains a visible red HeNe laser that is used as a convenient sighting tool to verify the alignment of the laser beams and optical arrangements and to position the calorimeter and simulant. However, in this work the beams were aligned with their respective sensors by placing clear plexiglass in front of the sensors and exposing the plexiglass to the CO₂ laser just enough to etch the patterns of the beams onto the plexiglass. These patterns were used to center the calorimeter and simulant in their respective beam paths. The beam area was measured from the burn profile and used in future power density calculations.

The first experiments were designed to compare the beam power measured by a calorimeter in the primary beam path to the beam power measured by the calorimeter in the secondary beam path under identical lasing conditions. This was accomplished by aligning a calorimeter in the primary beam path and firing the laser. The same calorimeter was then moved to the secondary beam path and identical test conditions repeated. A relationship was developed between the beam power in the two paths, which allowed a power reading from one path to be converted to the other path.

To calibrate the skin simulants, a simulant was mounted in the primary beam path and a calorimeter in the secondary beam path. Plexiglass panels were etched with the CO₂ beam and used to check the alignment of the sensors and record the beam area.

The two sensors were irradiated simultaneously and their output recorded and stored in the Compaq 320C2 PC. This procedure was repeated for a number of different laser powers and pulse durations.

D. Analysis

The output signals from the calorimeter and simulant required further formatting because the signals from these sensors were in terms of voltage and not in the desired units of temperature ($^{\circ}\text{C}$) and $\text{cal}/\text{cm}^2\text{-s}$.

The voltages were converted to temperature values using a nested polynomial relationship. This relationship is

$$T = 0.1008609 + (X/G) * (25729.9 + (X/G) * (-767345.8 + (X/G) * (78025595.8 + (X/G) * (-9.25e9 + (X/G) * (6.97e11 + (X/G) * (-2.66e13 + (X/G) * (3.94e14))))))), \quad (4)$$

where T is temperature, X is the voltage reading from Labtech Notebook, and G is the EXP-16 Multiplex gain setting. A Lotus 1-2-3 file called (TEMPCONV) was created as a template file. Using Eq. 4, the data imported was automatically converted to $^{\circ}\text{C}$ and then normalized to a room temperature of 22°C .

A similar method was used to convert the calorimeter readings from voltage to $\text{cal}/\text{cm}^2\text{-s}$. Each calorimeter was supplied with a calibration curve that related the calorimeter's output voltage with $\text{Btu}/\text{ft}^2\text{-s}$. These curves were linear with a y-intercept of zero, so the slope of each curve was used as a multiplier to convert from voltage to $\text{Btu}/\text{ft}^2\text{-s}$.

The following relationship was developed to convert this value to $\text{cal/cm}^2\text{-s}$:

$$q = ((X/G) * M * 3600 * 1000 * 0.00007535) / (B * A * P) \quad (5)$$

where q is the power density, M is calorimeter multiplier, B is the absorptivity of the calorimeter, A is the surface area of the laser beam on the skin simulant, and P is the conversion factor from the secondary to the primary beam path. Equation 5 was used to convert the voltage recorded by the calorimeter to the power of the beam impinging on the skin simulant. Before the sensors were irradiated the laser pulse power reading was zeroed to account for the dc offset of the calorimeter. A Lotus 1-2-3 template file, CALORIM2, was created to automatically convert the imported data file containing the voltage signals into units of $\text{cal/cm}^2\text{-s}$ at the simulant and also in watts at the calorimeter.

EXPERIMENTAL AND ANALYTICAL RESULTS

To find the relationship between the power in the primary beam path and the secondary beam path, tests were conducted using different calorimeters and powers. The results for six tests using three different calorimeters and the resultant conversion factor are shown in Table 2. From these data, the average conversion factor from secondary beam power to primary beam power that was used in Eq. 5 was 0.733. Figure 2, illustrates the primary and secondary path powers of a calorimeter after being analyzed through Lotus 1-2-3.

Table 2. Beam Path Comparison Results

<u>Calorimeter #</u>	<u>Primary</u> <u>(cal/cm²-s)</u>	<u>Secondary</u> <u>(cal/cm²-s)</u>	<u>S/P (%)</u>
44676	3.96	2.94	74.2
44676	3.80	2.72	71.6
44674	6.25	4.43	70.8
44674	5.49	4.16	75.0
44677	5.23	3.87	74.1
44677	4.89	3.62	73.9
<u>Final Average:</u>			<u>73.3</u>

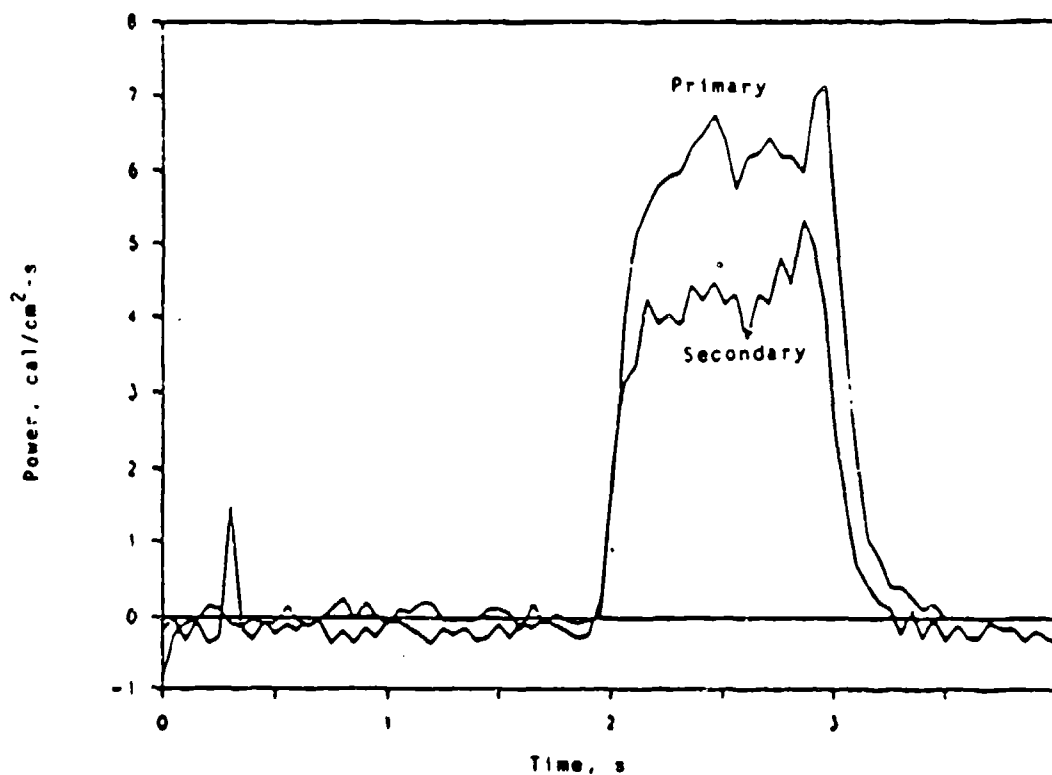


Fig. 2. Calorimeter #44674, Primary and Secondary Path Powers.

Skin simulant calibrations were conducted for a variety of skin simulants using different beam powers, pulse durations, calorimeters, and experimental conditions. Included in this report are several examples of the resulting calibration curves that show the experimental and theoretical results. The parameters used in Labtech Notebook are shown in Table 3. The calorimeter used is listed with each figure. Figures 3 through 6 are the actual calibration curves.

Table 3. Calibration parameters used in Fig. 3.

Sampling rate:	30.0 Hz
Sampling duration:	8.0 s
EXP-16 gain:	100.0
Cal multiplier(#44677):	6.3 mV/(Btu/ft ² -s)
Cal absorptivity:	82.0%
S-P conversion:	0.733
Beam area:	3.71 cm ²

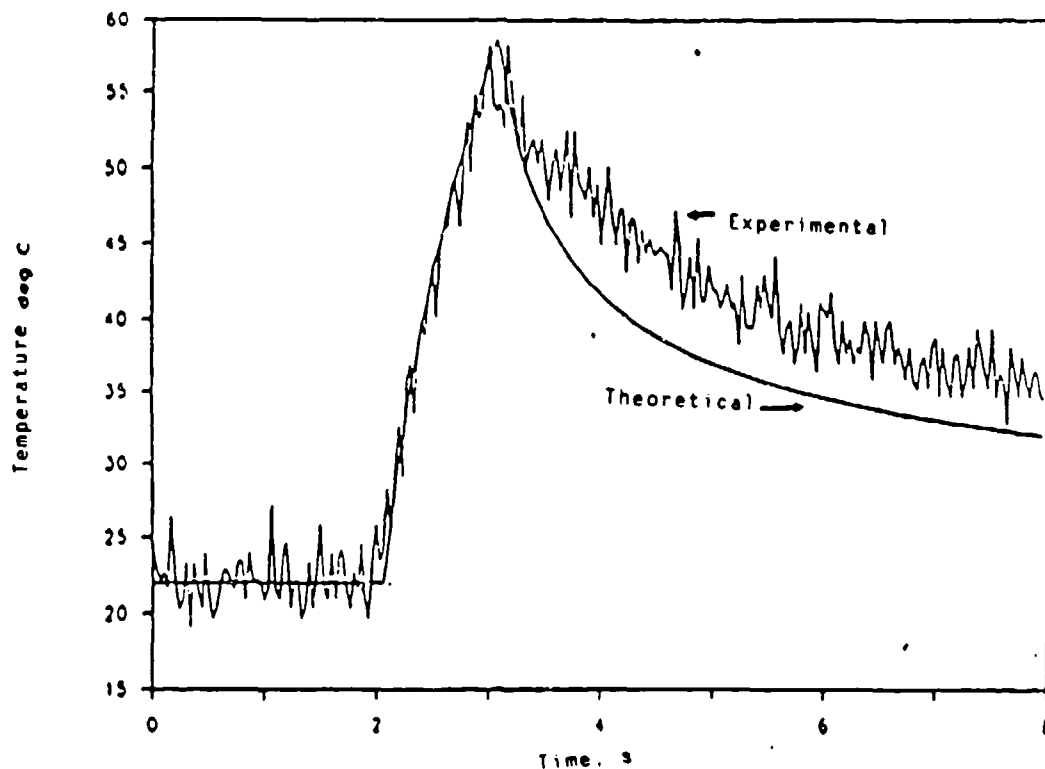


Fig. 3. Skin Simulant, Experimental and Theoretical Curves.
Calorimeter #44677, $1.384 \text{ cal/cm}^2\text{-s}$, 1 s pulse.

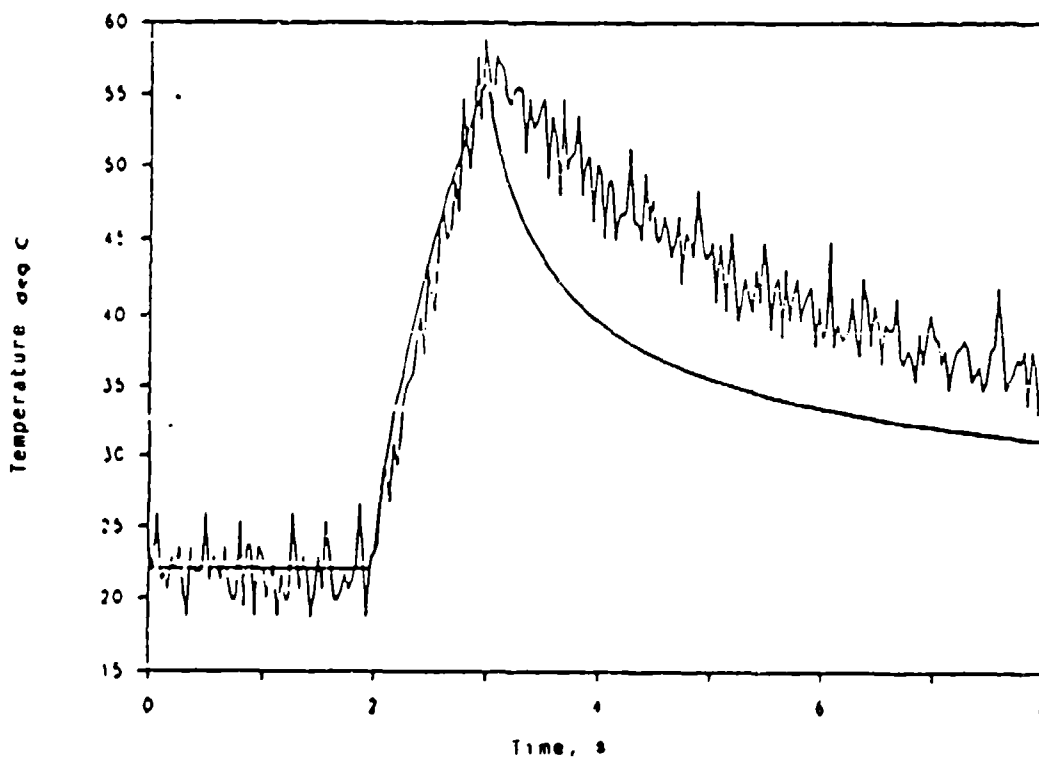


Fig. 4. Skin Simulant, Experimental and Theoretical Curves.
Calorimeter #44676, $1.278 \text{ cal/cm}^2\text{-s}$, 1 s pulse.

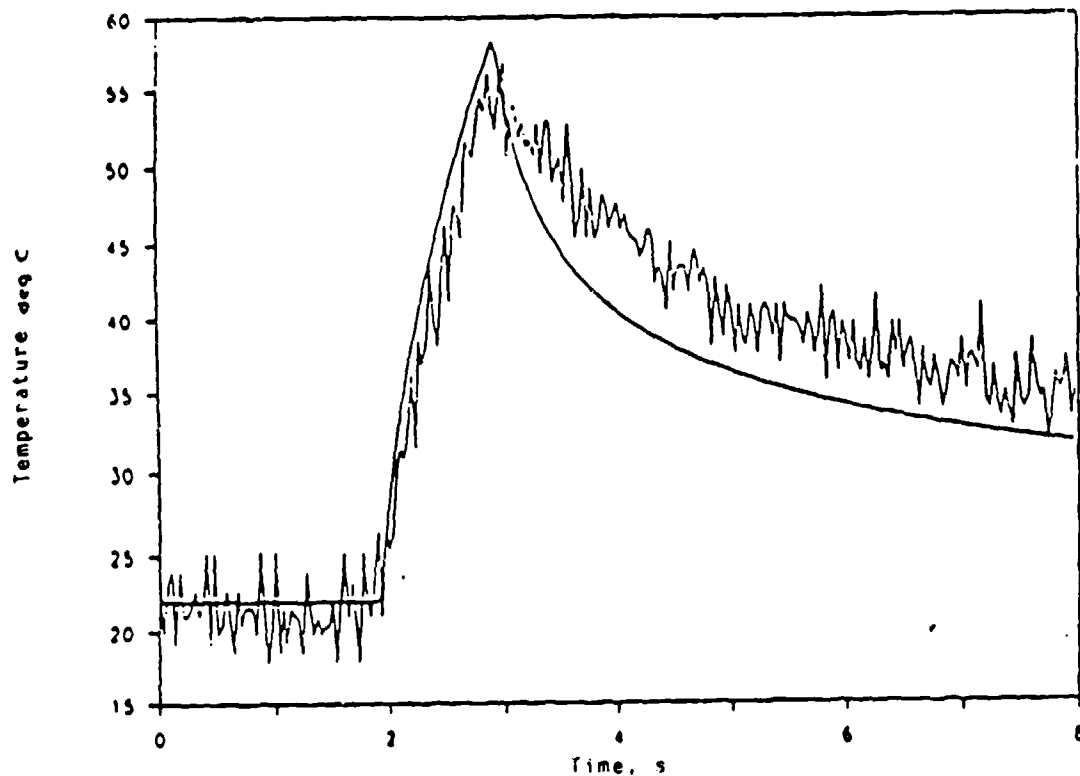


Fig. 5. Skin Simulant, Experimental and Theoretical Curves.
Calorimeter #44674, $1.38 \text{ cal/cm}^2\text{-s}$, 1 s pulse.

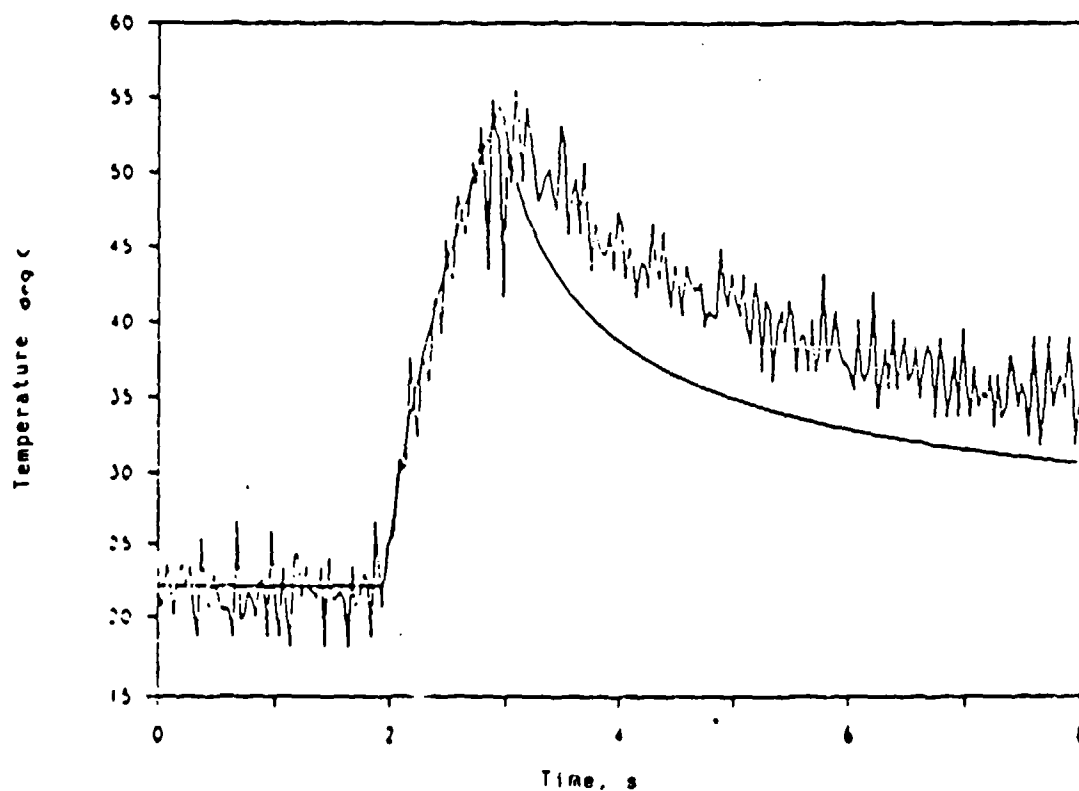


Fig. 6. Skin Simulant, Experimental and Theoretical Curves
Calorimeter #44677, $1.23 \text{ cal/cm}^2\text{-s}$, 1 s pulse.

CONCLUSIONS AND RECOMMENDATIONS

The thermal response of silica filled, α -cellulose urea formaldehyde skin simulants can be compared to the thermal damage in human skin. A computer program can be written in BASIC to record and compare the thermal parameters of skin with those of the skin simulant. The CO_2 laser can be used as a thermal radiation simulator for the calibration of skin simulant sensors. More precise results can be achieved by collecting data simultaneously from the thermal source and the sensors using a two-path optical system.

It is recommended that the procedure described in this report be used to calibrate silica filled, α -cellulose urea formaldehyde skin simulants.

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APPENDIX: BASIC Program (SIMTHR30)

```

10 REM dimension statements, values of the skin constants, time between points
20 REM (.001) sec, time of calculation: 7 seconds
30 DIM E(300), O(300), Q(300), W(300), R(300), X(300)
    REM THERMAL PARAMETERS OF ACTUAL SKIN, Q IS NUMBER OF ITERATIONS
38 E=0: Q=210: B=.00015: Z=.01
40 K=.00122: R=1.03: C=.87
43 REM ROOM TEMPERATURE IS SET TO 22 C AND HAS A 1 SEC PAUSE BEFORE THE
44 REM PULSE BEGINS. DATA RATE CORRESPONDS TO A SAMPLING RATE OF 30HZ
45 OPEN "o", #1, "c:\nb\newstuff\therdata.prn"
46 FOR J = 1 TO 30
47 PRINT #1, "22"
48 NEXT J
60 REM ENTER IRRADIANCE (CAL/CM2) AND PULSE LENGTH (SEC)
70 INPUT "IRRADIANCE, CAL/CM2 H=", H
80 INPUT "PULSE LENGTH, SEC T=", T
90 AS = 1
100 REM CALCULATE VALUES FOR INTRODUCTION TO HEAT FLOW EQUATION
110 A=K/(R*C)
120 F=Z/(2*(SQR(A)))
130 D=B*Z/K
140 E=A*(B)^2/K^2
150 REM CALCULATE ERFC
155 REM L IS THE DESIRED TIME STEP TO MATCH A SAMPLING RATE
160 L=1/30
170 REM CALCULATE TEMPERATURE
180 FOR W=1 TO Q+1
190 S=1: O=0: V=0
200 REM CALCULATE ERFC VALUES
210 FOR I=0 TO 26
220 P=(-1)^I*(F/SQR(L)^((2*I)+1))
230 M=(-1)^I*(F/SQR(L)+(B/K)*SQR(L*A))^((2*I)+1)
240 J=((2*I)+1)*S
250 PA=P/J
260 N=M/J
270 S=S*(I+1)
280 V=V+PA
290 O=O+N
300 NEXT I
310 L=L+(1/30)
320 V=1-V*(2/SQR(3.1416))
330 O=1-O*(2/SQR(3.1416))
340 Q(W)=(H/B)*(V-O*(EXP(D))*EXP(E*L))
350 X(W)=(1/30)*W
360 PRINT "CALCULATING", W
370 NEXT W

```

APPENDIX: BASIC Program (SIMTHR30) (Cont'd)

```
380 REM CALCULATE NEXT TEMPERATURE
390 REM CALCULATE NEXT TEMP VALUES FROM END OF PULSE USING VALUES FROM
400 REM BEGINING PULSE AND PLACE IN STORAGE
410 FOR I=30*T TO Q+1
420 R(I+1)=Q(I-(30*T-1))
430 REM CALCULATE TEMP VALUES FROM T=0 TO 7 SECONDS, SUBTRACT VALUES
440 REM OT T=0 TO PULSE LENGTH STARTING AT PULSE END
450 NEXT I
470 FOR I=1 TO Q+1
480 Q(I)=Q(I)-R(I)
490 Q(I)=Q(I)+22
500 PRINT #1,Q(I)
510 NEXT I
520 END
```

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